

FLIGHT TESTING TIME AND ENERGY MANAGED OPERATIONS (TEMO)

Ronald Verhoeven¹, Frank J.L. Bussink¹,
Netherlands Aerospace Centre (NLR), Amsterdam, The Netherlands
Xavier Prats², Ramon Dalmau³
Technical University of Catalonia (UPC), Barcelona, Spain

From 9-26 October 2015 the Netherlands Aerospace Centre (NLR) in cooperation with Delft University of Technology (TUD) has executed Clean Sky flight trials with the Cessna Citation II research aircraft. The trials consisted of several descents and approaches at the Eelde airport near Groningen, demonstrating the TEMO (Time and Energy Managed Operations) concept developed in the Clean Sky Joint Technology Initiative research programme as part of the Systems for Green Operations (SGO) Integrated Technology Demonstrator.

A TEMO descent aims to achieve an energy-managed idle-thrust continuous descent operation (CDO) while satisfying ATC time constraints, to maintain runway throughput. An optimal descent plan is calculated with an advanced on-board real-time aircraft trajectory optimisation algorithm considering forecasted weather and aircraft performance. The optimised descent plan was executed using the speed-on-elevator mode of an experimental Fly-By-Wire (FBW) system connected to the pitch servo motor of the Cessna Citation II aircraft. Several TEMO conceptual variants have been flown. It has been demonstrated that the TEMO concept enables arrival with timing errors below 10 seconds. The project was realised with the support of CONCORDE partners Universitat Politècnica de Catalunya (UPC) and PildoLabs from Barcelona, and the Royal Netherlands Meteorological Institute (KNMI).

I. ABBREVIATIONS

AGL	Above Ground Level
A/P	Auto Pilot
A/T	Auto Throttle
ATC	Air Traffic Control
ATS	Air Transportation System
CDO	Continuous Descent Operation
CTA	Controlled Time of Arrival
CTI	Controlled Time Interval
EFIS	Electronic Flight Instrument System
FAP	Final Approach Point
FAS	Final Approach Speed
FBW	Fly By Wire
FMS	Flight Management System
FTIS	Flight Test Instrumentation System
G/S	Glide Slope
HMI	Human Machine Interface
IAF	Initial Approach Fix
ILS	Instrument Landing System
KNMI	Royal Netherlands Meteorological Institute

¹ Researcher, AOCF, Anthony Fokkerweg 2, Amsterdam, The Netherlands

² Associate Professor, EETAC-UPC, Castelldefels (Barcelona), Spain.

³ PhD student, EETAC-UPC, Castelldefels (Barcelona), Spain.

ND	Navigation Display
NLP	Non Linear Programming
NLR	Netherlands Aerospace Centre
PFD	Primary Flight Display
RFMS	Research Flight Management System
S/B	Speed Brake
SoE	Speed on Elevator
RWY	Runway
TED	Time & Energy Display
TEMO	Time and Energy Managed Operations
THR	Runway Threshold
TMA	Terminal Manoeuvring Area
ToD	Top of Descent
TRL	Technology Readiness Level
TUD	Delft University of Technology
UPC	Polytechnic University of Catalonia
VSD	Vertical Situation Display

II. INTRODUCTION

The expected growth in air traffic combined with an increased public concern for the environment, have forced legislators to rethink the current air traffic system design. The current air traffic system operates at its capacity limits and is expected to lead to increased delays if traffic levels grow even further. Both in the United States and Europe, research projects have been initiated to develop the future Air Transportation System (ATS) to address capacity, and environmental, safety and economic issues. To address the environmental issues during descent and approach, a novel Continuous Descent Operations (CDO) concept, named Time and Energy Managed Operations (TEMO), has been developed co-sponsored by the Clean Sky Joint Undertaking. It uses energy principles to reduce fuel burn, gaseous emissions and noise nuisance whilst maintaining runway capacity. Different from other CDO concepts, TEMO optimizes the descent by using energy management to achieve a continuous engine-idle descent, while satisfying time constraints on both the Initial Approach Fix (IAF) and the runway threshold. As such, TEMO uses time-metering at two control points to facilitate flow management and arrival spacing.

TEMO is in line with SESAR step 2 capabilities, since it proposes 4D trajectory management and is aimed at providing significant environmental benefits in the arrival phase without negatively affecting throughput, even in high density and peak-hour operations. In particular, TEMO addresses SESAR operational improvement (OI) TS-103: Controlled Time of Arrival (CTA) through use of datalink [1].

TEMO has been validated starting from initial performance batch studies at Technology Readiness Level (TRL) 3, up to Human-in-the-Loop studies in realistic environments using a moving base flight simulator at TRL 5 ([2]-[6]).

In this paper the definition, preparation, performance and analysis of a flight test experiment is described with the objective to demonstrate the ability of the TEMO algorithm to provide accurate and safe aircraft guidance toward the Initial Approach Fix (IAF), and further down to the Stabilization Point (1000 ft AGL), to demonstrate the ability of the TEMO algorithm to meet absolute time requirements at IAF and/or runway threshold and to evaluate the performance of the system under test (e.g. fuel usage).

The outline of this paper is as follows: the next session discusses the Time and Energy Managed Operations (TEMO) concept. In Section IV a description is provided of the set-up of the flight trials and test equipment. Section V discusses the results of the trials by assessing the measured data and gathered pilot feed back. The final section comes to conclusions.

III. TIME AND ENERGY MANAGED OPERATION (TEMO)

The core principle of the TEMO concept is that the energy of the aircraft (speed and altitude) is managed in such a way that the ATC time requirements are fulfilled: speed on elevator is used to convert potential energy into kinetic energy at the appropriate rate. An optimization process determines the best energy trajectory, which minimizes the use of throttle and speed brake. TEMO implies that speed and vertical profiles are dynamically adjusted along the descent in case time and/or energy deviations exceed some predefined thresholds.

In the TEMO concept of operations the optimal descent trajectory is computed by the FMS while the aircraft is in cruise, well before the Top of Descent (ToD). The descent is optimized with respect to thrust (i.e. zero throttle) and speed brakes and incorporates applicable standard operational procedures. The optimal outcome is not a fixed vertical trajectory from ToD to ILS glideslope intercept, as generated in current FMS implementations, but a speed plan, implying a preplanned speed as a function of distance to prescribed points along a fixed arrival routing. The FMS will be triggered to re-plan the trajectory when the following occurs:

- ATC may request the aircraft to fulfil a specific time requirement at the Initial Approach Fix (IAF) or at the runway threshold.
- Due to model inaccuracies, meteorological uncertainties or flight guidance errors, the aircraft may deviate from the planned trajectory. TEMO algorithms continuously monitor time and energy errors (in terms of potential and kinetic energy) at the current position. When the errors exceed some allowable error margin, a new trajectory is calculated from the aircraft current state to the runway threshold.

In both cases, the trajectory re-planning consists of initiating an optimization algorithm aiming at minimizing throttle and speed brake usage; at the same time the ATC time requirements (if applicable) are fulfilled.

Note that any sustained time and/or energy error could also be resolved using tactical guidance, which also monitors the time and energy errors but takes immediate action to resolve the observed error by commanding calibrated airspeed and/or thrust changes to nullify the error. The Continuous Descent Approaches for Maximum Predictability concept [7], uses a similar tactical approach by using a groundspeed control-law to solve accumulated errors during the execution of an idle descent. The current implementation of TEMO can use both strategic or tactical guidance methods, which was also subject of study in these trials.

From an ATC point of view, the TEMO concept assumes that the arrival management automation will use available trajectory information to determine the preferred landing route, landing sequence, inter-aircraft spacing, and arrival schedule based on the capabilities and constraints of the inbound aircraft, as well as the scheduled airport constraints (such as runway configuration, mixed-use runway use, dependent approaches, and weather conditions). The scheduling process will be coordinated with adjacent ATC centres and when the schedule is frozen a fixed RNAV arrival route (to the runway) with Controlled Time of Arrival (CTA) at the IAF (or other relevant points) will be provided.

When entering the TMA, ATC may either complement or substitute the CTA instruction with a CTA at the runway threshold or a Controlled Time Interval (CTI) instruction to facilitate relative spacing between the own aircraft and a designated aircraft ahead. The assigned control times will be entered into the aircraft's system and used as time requirements by the on-board TEMO toolset which resides in the on-board Flight Management System (FMS).

The FMS may also compute the so-called Earliest and Latest trajectories at the runway threshold (and/or IAF). They have an important operational value, since they will allow the aircraft crew to know the feasible time window at the runway threshold (and/or at the IAF). Thus, knowing these lower and upper time bounds the aircraft crew will be able to accept or reject the requested CTA/CTI.

Along the descent the crew will monitor the operation and configure the aircraft as directed by the guidance application. Separation responsibility will remain with ATC as no transfer of responsibility will take place.

TEMO operations will cease, when the aircraft is on the correct lateral and vertical path and in the desired landing configuration and thrust is stabilized and set to maintain the target Final Approach Speed (FAS). This stabilization point is targeted at 1000 ft above threshold elevation.

IV. FLIGHT TEST SETUP

The following section outlines the flight test setup in terms of objectives, equipment, HMI, scenarios and flights.

A. Objectives

The main objectives of the TEMO trials were:

- Demonstrate the ability of the TEMO algorithm to provide accurate and safe aircraft guidance toward the Stabilization Point (1000ft AGL).
- Demonstrate the ability of the TEMO algorithm to meet absolute time requirements at IAF and/or runway threshold.
- Obtain pilot feedback on operational and safety aspects
- Collect data to allow for TEMO performance evaluation

B. Test aircraft

The test aircraft was a Cessna Citation II aircraft (Figure 1), jointly operated by Netherlands Aerospace Centre (NLR) and Delft University of Technology (TUD).



Figure 1 Test aircraft

The test aircraft has had an advanced cockpit upgrade in 2011 with the installation of a Rockwell Collins Pro Line 21 Electronic Flight Instrument System (EFIS). The test aircraft is equipped with an Universal Avionics Flight Management System (FMS) for managing lateral navigation. The aircraft may be operated single pilot. Optionally on the right side of the cockpit experimental display(s) may be installed by replacing one or both Pro Line EFIS displays.

C. Experimental equipment

The architecture of the on-board implementation of the TEMO concept is depicted in Figure 2. At the core is the TEMO trajectory optimiser in the Research Flight Management System (RFMS) application. The implementation of the TEMO trajectory optimiser used in these flight trials is calling the advanced CONOPT nonlinear programming (NLP) optimiser to solve the large scale optimisation problem. Within the RFMS also the TEMO time and

energy deviation monitoring take place, and triggering of replans when required. Furthermore, the weather tool called WEMSGEN processes the available weather forecast into spline coefficients suitable as input for the trajectory optimiser. The weather tool accepts as input GRIB formatted forecast data provided by the Royal Netherlands Meteorological Institute (KNMI) or in-flight measured data collected by the test aircraft during a run. Both, the optimiser and the weather tool have been developed by the Clean Sky FASTOP consortium.

To execute an optimised trajectory, its speed plan should be followed in Speed-on-Elevator (SoE) mode and its thrust/speed brake plan (read: energy plan) preferably using an Auto Throttle/ Auto Speed Brake system.

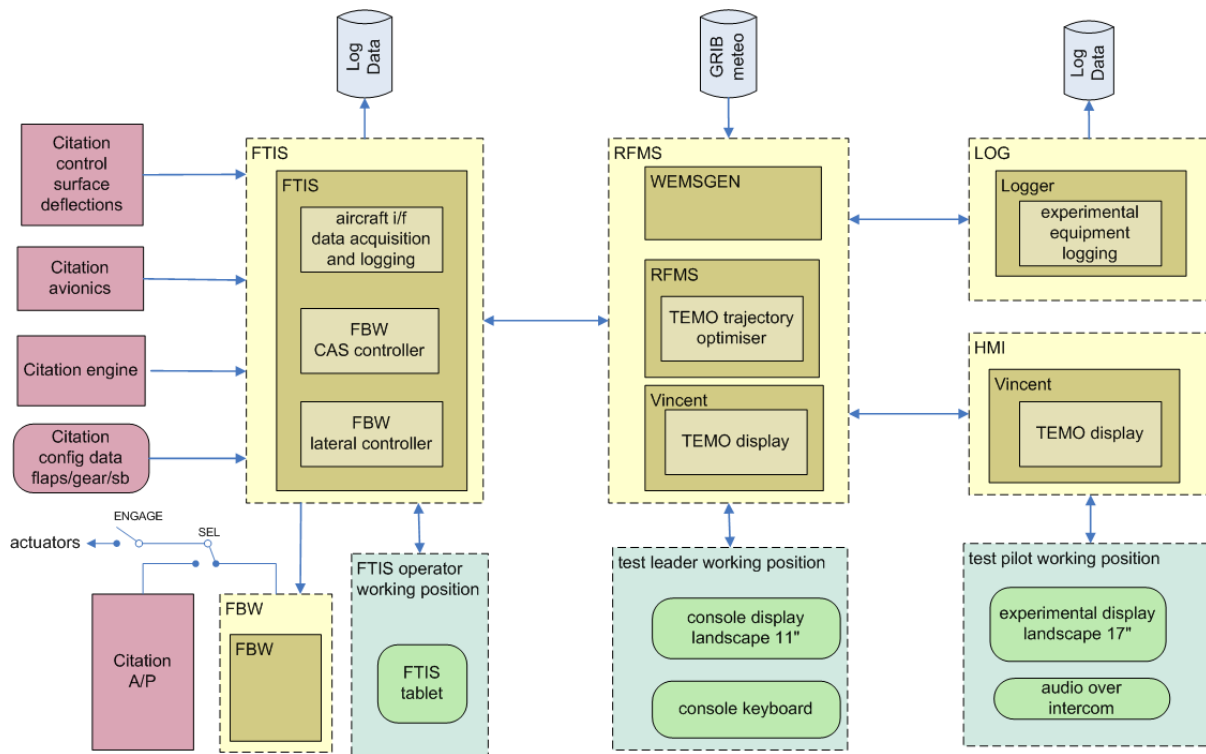


Figure 2 Architecture of on-board TEMO implementation

In the test aircraft no Auto Throttle or Auto Speed Brake system is available. Therefore the energy plan is followed manually by the test pilot using graphical cues on the experimental display in the cockpit. The speed plan is flown using an experimental Fly-By-Wire (FBW) system developed by the TUD. If the FBW system is active, the Citation A/P is disconnected and the actuators are controlled by the FBW system. The input signals of the FBW are calculated by the Flight Test Instrumentation System (FTIS) based upon the optimised speed plan as provided by the RFMS. The FBW input signals for lateral navigation are based upon lateral guidance signals given by the RFMS. In addition, the FTIS functions as an interface to the Citation aircraft for the experimental equipment, and incorporates data logging functionality. A dedicated platform is generating the TEMO HMI for the cockpit touch screen display (Figure 3). The TEMO HMI has been implemented using an NLR in-house developed display prototyping tool called Vincent. Vincent enables quick and flexible avionics display prototyping for evaluation purposes. The LOG platform was responsible for logging all data generated by the experimental equipment. The FTIS, RFMS, LOG and HMI computer platforms were all installed in 17" racks mounted in the back of the Citation cabin (Figure 4).



Figure 3 Experimental cockpit display



Figure 4 Experimental equipment in back of Citation cabin

D. Cockpit TEMO HMI

In Figure 5 the TEMO cockpit HMI variant is shown for the case that time and energy deviations are both compensated for by triggering replans (strategic guidance). The HMI consists of a Primary Flight Display (PFD), Navigation Display (ND), Vertical Situation Display (VSD) and a Time & Energy Display (TED). On left side of the TED two vertical bar indicators indicate the current energy and time deviation by an magenta dot and the current allowed margins in green at the top and bottom of the bars. The third bar indicator shows the planned and actual N1, and the most right bar indicator shows the planned and actual Speed Brake (SB) action. The planned N1 and SB cues on the display were used by the test pilot to “simulate” an Auto Throttle and Auto Speed Brake system.

Furthermore, the TEMO calculated speed is indicated by a magenta dot on the PFD speed tape, and the TEMO predicted altitude on the PFD altitude tape, both by a magenta dot. In addition, cues were provided on the PFD to timely indicate aircraft configuration changes. The thick parts of the green route/profile line on the ND and VSD indicate segments where non-idle thrust is planned.

F. Altitude and speed profile

In Figure 7 a typical altitude (red) and speed (blue) profile is shown generated enroute before the first ATC time constraint is included. As already mentioned, the speed profile after ToD is followed in SoE mode with idle thrust. The trajectory optimiser takes care that the generated speed profile complies with all relevant flight operational constraints and with all ATC constraints as defined for considered arrival and approach procedure. The resulting speed margin is shown as light blue area around the blue speed profile line.

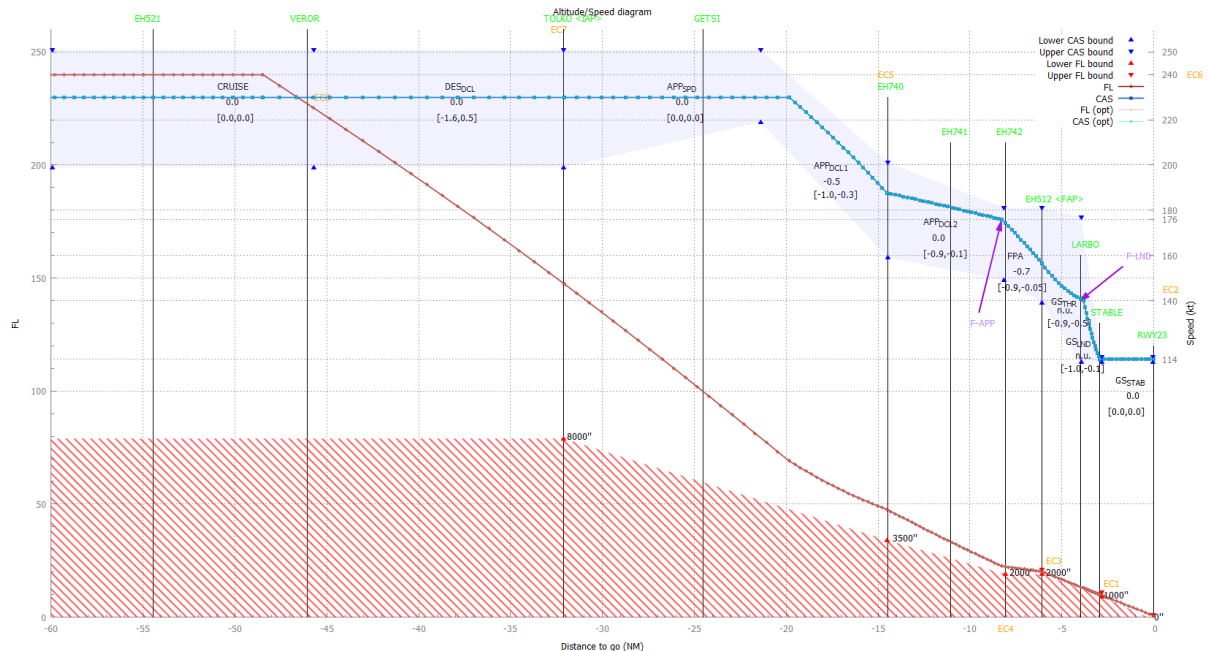


Figure 7 Typical altitude and speed profile

G. Flights and Scenarios

The Clean Sky Citation flight trials took place in the period from 9th till 26th of October 2015. In total 9 flights were performed: 3 shakedown flights and 6 test measurement flights. Four test pilots were involved.

Generally, in a measurement flight a maximum of 3 á 4 runs may be performed. The following three TEMO guidance variants have been tested:

- Time and Energy both strategical (Ts-Es)
- Time tactical and Energy strategic (Tt-Es)
- Time and Energy both tactical (Tt-Et)

Together with the FMS step baseline variant this makes in total 4 conceptual variants. Each variant has been tested for four different pairs of Controlled Time of Arrival (CTA) at the IAF/Runway Threshold relative to the Estimated Time of Arrival (ETA) obtained in absence of any timing requirements: 0/0, +30s/+15s, +20s/+10s, and -20s/-10s. So, consequently, 16 different scenarios can be identified, if we define a scenario by the conceptual variant considered together with the CTA pair imposed. All 16 scenarios have been tested at least once. Test pilots were tasked to fly the aircraft by monitoring/controlling speed, thrust, and speed brake action, following the TEMO related cues on the PFD and TED display. Entering incoming CTAs from ATC were performed by the experiment leader seated in the cabin.

Note that during all *first* runs in a measurement flight, the weather forecast provided by the KNMI was used by the trajectory optimiser. In the succeeding runs, in-flight measured weather data of the previous run was used as weather forecast.

V. ASSESMENT RESULTS

A. Time Performance and Efficiency

Time deviations at the IAF were relatively small. In all runs absolute time errors at the IAF stayed within 5 seconds.

In Figure 8 the time deviation at the runway threshold and the fuel consumption between EH522 and runway threshold are shown. When we compare these time deviations with the time deviations at the Final Approach Point (FAP), as shown in Figure 9, then it is noticed that in the last part of the flight on the G/S, time deviations increased with respect to the deviations at the FAP. In almost all runs the aircraft arrives earlier than planned. Underlying causes are

- Aircraft speed deviations from planned speed due to performance model inaccuracies and guidance inaccuracies (manual flown)
- Wind forecast errors on the G/S

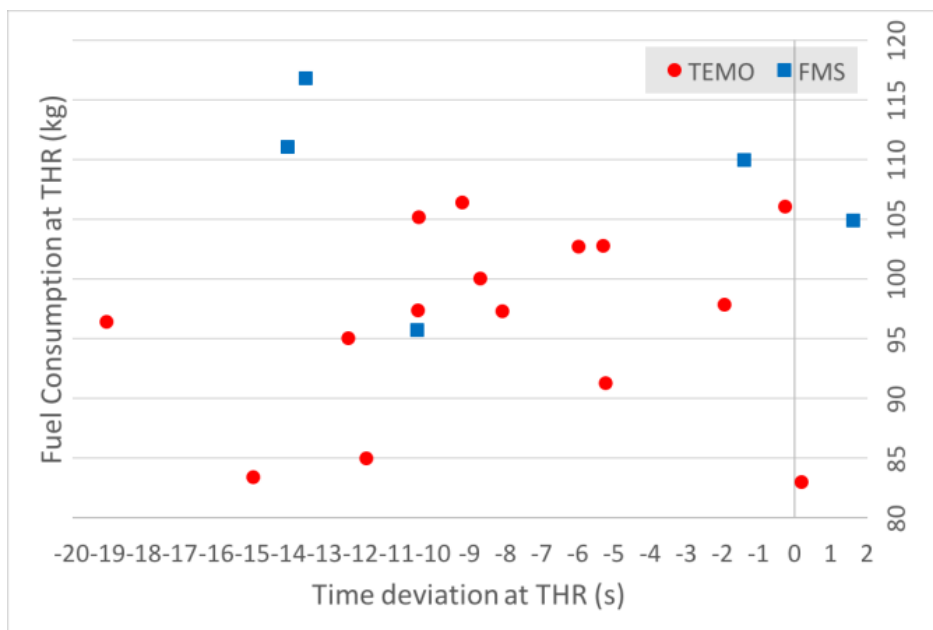


Figure 8 Time deviation and fuel consumption at runway threshold

Furthermore, we observe that in general timing at the FAP for TEMO runs is more accurate than for the FMS runs.

Note that on the G/S time deviations were not corrected anymore (either strategically or tactically).

Also, with respect to efficiency it is observed that in general TEMO runs reaching lower values of fuel consumption than FMS runs.

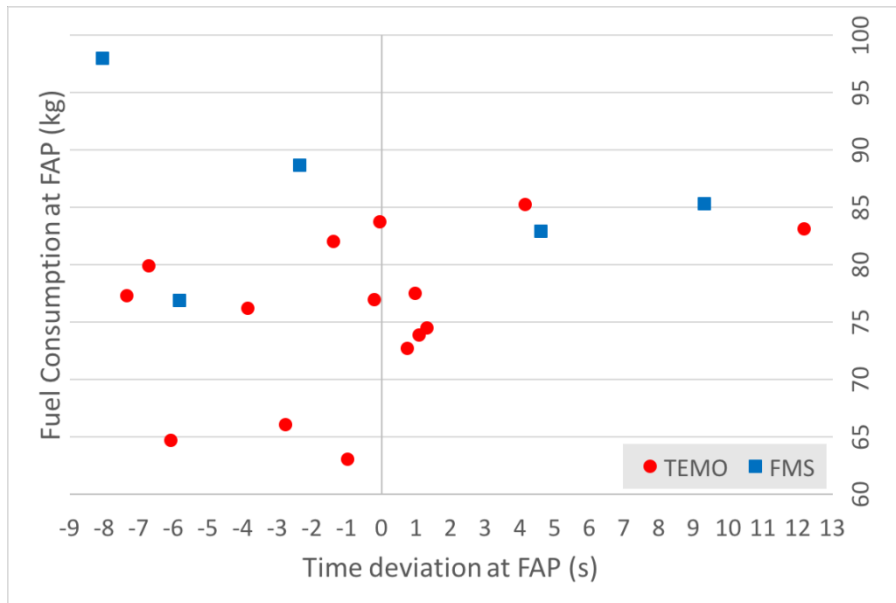


Figure 9 Time deviation and fuel consumption at FAP

B. Flight operational and safety aspects

After each run during flight, and after each flight in the debriefing, flight crew were questioned and comments were gathered. In general, the TEMO flight operation was assessed by the test pilots as safe and acceptable. However the following observations and comments were made with respect to TEMO *planning* aspects:

- The *transition phase* of a plan was in some cases too dynamic. Too large vertical speed and IAS changes in a relatively short time were planned, which couldn't be properly followed by the aircraft. This situation may even trigger another re-plan, which is not desirable. The transition phase of a plan is the first part of a replan of limited duration (maximal 20 seconds) to "connect" the aircraft current state to a state appropriate for the phase of flight. This issue can be addressed by tuning the parameters in the trajectory optimiser associated with this phase.
- In a few runs the *number of replans* was considered too large by the test pilots (more than 10 replans). This makes a descent too much unpredictable and therefore less operationally acceptable. It was recommended by the test pilots to limit the number of replans during descent.
- In a few occasions the *required calculation time* to replan, was larger than expected (more than 20 seconds). It was recommended by the test pilots to limit the calculation time to 20 seconds.
- *Anti-icing* was not considered in the plan, however the resulting delta in the thrust settings has a significant effect on the energy state of the aircraft, and therefore should be taken into account when optimising the descent trajectory.

And with respect to TEMO *guidance* aspects, it was observed that:

- Speed plan used for *vertical guidance*, was followed well (mean speed error within 1 kt).
- During shakedown flights, the *lateral guidance* provided by the experimental FMS appeared to be not suitable as input for the FBW lateral controller. Therefore it was decided to use Citation FMS for lateral guidance in the measurement flights.

- It was observed that the planned route was followed well, although the actual distance flown was in most runs a bit larger than the distance planned.
- *Interception at ILS G/S* sometimes not properly performed. In some runs the G/S was attempted to intercept from below, but by following the TEMO calculated speed and energy plan, the aircraft would not intercept but instead stay below the G/S. This issue can be addressed at procedural level in various ways.
 - *TEMO Es-Ts guidance variant* gives in general least nr of replans. This can be explained by recalling that the tactical time controller add a delta speed on top of the optimal calculated speed, to compensate for an observed time deviation. By flying another speed than planned, the aircraft's energy state will start to deviate from the planned energy and therefore trigger a replan once the allowed energy margin is impaired.

Note that except for the ILS G/S interception, all of the above listed observations or comments which needs to be addressed, are at implementation level.

Finally it is mentioned that the TEMO HMI was received well by the test pilots. Most of the pilots are comfortable with the TEMO visual indicators displayed and consider they are very useful and necessary. In general the test pilots were able to follow the N1 and speed brakes indicators very well. The altitude and time energy indicators were well appreciated by the pilots and they expressed it was an intuitive way to understand why a plan is working, and when to expect a replan.

C. Flight testing aspects

At various levels, the TEMO real aircraft flight trials were more complex as the earlier performed TEMO high fidelity simulation experiment in the NLR GRACE flight simulator [6]:

- Environment conditions (e.g. wind, temp, pressure) are less controlled.
- Testing the various different TEMO variants in one flight lead in some occasions to flight crew confusion in between the different test runs: which TEMO cues to follow in current phase of flight? What is the TEMO system trying to achieve? To support the flight test crew it is recommended to provide more crew training for these type of test trials.
- Implementation aspects which required tuning during trial execution (i.e. parameters of the optimiser, speed controller parameter tuning, and the lateral guidance functionality)
- Procedural adjustments during trial execution (i.e. the FMS base line procedure, and G/S intercept procedure)

Clearly, when testing such a complex experimental system (s/w, procedure design, execution modes, HMI, avionics interfaces, ...etc) a large number of unexpected issues can occur. To mitigate this risk for this type of trials, the number of shakedown flights should be increased and/or the time period in between shakedown flights enlarged.

In addition, it is important to make a distinction between conceptual aspects and implementation related aspects in these test trials. For example, on the test platform certain TEMO supporting automation was not available, such as e.g. auto throttle and auto speed brake functionality. This had an impact on the HMI, cockpit procedures and pilot workload, which should be taken into account when interpreting the data results.

VI. CONCLUSION

Although the test platform had some constraints and limitations due to the lack of some TEMO supporting automation, the TEMO concept has been successfully tested in a real-world environment with positive results and feedback of participants.

The flight trials have indicated that two aspects at conceptual level of a TEMO flight operation require further attention: the ILS G/S interception and managing time deviations on the ILS Glide Slope. Both aspects are solvable and needs to be addressed in a next step.

Furthermore, the flight trials have demonstrated that TEMO flight operations are safe and pilot acceptable. It has been demonstrated the accurate timing can be achieved while preserving fuel benefits in line with current day fuel consumption of CDAs. A promising prospect that indicates that the capacity challenge can be addressed while greening aviation!

VII. ACKNOWLEDGEMENTS

The research leading to these results received cofunding from the Clean Sky Joint Technology Initiative under Grant Agreement no. CSJU-GAM-SGO-2008-001.

The authors acknowledge the contributions of Alexander in't Veld, Hans Mulder, Olaf Stroosma, Erik-Jan van Kampen, Ferdinand Postema and Klaas Menno (all TUD) during preparation and execution of this flight trials. Furthermore, the support by Josep Montolio and Brent Day of PildoLabs, Barcelona, is acknowledged.

And the contribution of Wim Bonnee, Robert Tump, Erwin Dekker, Huib Schriemer, Ger Nielen, Ivo Wilmes, Con Kranenburg, Nico de Gelder and Michiel Valens (all NLR) are acknowledged. Also much appreciation goes out to the support of the Royal Netherlands Meteorological Institute KNMI and the ATC Tower of Eelde airport.

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IX. BIOGRAPHIES

Ronald Verhoeven is working at the NLR since 1992 and has been involved in a wide variety of research programs, in which he combined his long-term human factors experience with his acquired flight operational knowledge, in the field of HMI cockpit prototyping and ATM concept evaluation in the civil application domain.

Examples are the EUROCONTROL PHARE programme, in which an elaborate 4-D ATM concept was evaluated. In this programme, Ronald Verhoeven was in charge of the Airborne HMI project and developed together with the European partners an advanced cockpit HMI concept supporting the PHARE 4-D trajectory negotiation concept with ATC.

In the EU 6th Framework project OPTIMAL, he lead experiments evaluating time-based navigation and spacing of Continuous Decent Approach flight operations in NLR's the full mission research simulator GRACE. Furthermore he has been actively involved in the 6th Framework project ERAT in which Continuous Decent Approach flight operations are studied in combination with advanced ATC supporting tools. Currently he is involved in the Clean Sky JTI (Joint Technology Initiative) representing a public-private partnership between the EC and the industry, evaluating optimized "green" flight operations within the SESAR ATM concept.

Frank Bussink started working at NLR in 1999 as an operational research engineer at the Flight Simulation department. There he worked on different international ATM R&D projects, amongst others Free Flight FMS (3FMS), INTENT and the NASA/NLR Free Flight project. In January 2002 he joined NASA Langley Research centre as a research scientist to support studies into the NASA "Distributed Air/Ground Traffic Management" (DAG TM) concept and the Small Aircraft Transportation System (SATS) concept. The research included among other the development of Conflict Detection, Resolution and Prevention algorithms and studies into concepts for Oceanic In-Trail Procedure (ITP) and Airborne Precision Spacing. In 2007 he rejoined NLR as a subject matter expert on Aircraft Surveillance Applications Systems (ASAS) and continued his research on the development and testing of new concepts of operations that use Automatic Dependent Surveillance-Broadcast (ADS-B). Mr. Bussink holds a B.Sc. in Aeronautical Engineering and a B.Sc. in Computer Engineering.

Xavier Prats is an associate professor at the Technical University of Catalonia (UPC). M.Sc. degree in aeronautical engineering from the École Nationale de l'Aviation Civile (ENAC) in Toulouse (France) and Ms. Sc. degree in telecommunications engineering from Telecom Barcelona. Furthermore, he received his Ph.D. in Aerospace Science and Technology from UPC-BarcelonaTech. His main research interests include improving the performance and efficiency of aircraft operations as well as the air traffic management (ATM) system. He co-founded the Icarus research group at UPC and he is currently leading the air transportation research activities within it.

Ramon Dalmau Codina was born in Palamós (Catalonia) and is an Aeronautical engineer from the Polytechnic University of Catalonia (UPC), located in Castelldefels (Barcelona). He joined the university's research group as intern in March 2013 and collaborated in some on-going research activities related with aircraft trajectory optimisation and optimal control. In February 2014 he moved to the NLR for an internship, aiming at obtaining his Bachelor final degree project related with the same topics. Next, Ramon Dalmau enrolled the Master on modelling for science and engineering held at the Autonomous University of Barcelona (UAB). In his Master thesis, which was performed in the Catalan Center of Technology (EURECAT), the parameters of a multicopter were estimated by means of non-linear programming. Recently, he also gave lectures of Air transportation infrastructures and Airport and Airspace Management at the UPC. Finally, in September 2015 he enrolled UPC as PhD candidate in the doctoral program of Aerospace Science and Technology, being Dr. Xavier Prats his PhD advisor.